Determination of the strong coupling constant $\alpha_s(m_Z)$ in next-to-next-to-leading order QCD using H1 jet cross section measurements

Daniel Britzger
for the H1 Collaboration and NNLOJET
Eur.Phys.J.C 77 (2017), 791 [arXiv:1709.07251]

11th Annual Meeting of the Helmholtz Alliance "Physics at the Terascale"
DESY, Hamburg, Germany
28.11.2017

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Why α_s?

***Strong coupling α_s** enters in the calculation of every process that involves the strong interaction*

World average value

$\alpha_s(m_Z) = 0.1181 \pm 0.0011$ [PDG2016]
~0.9% relative uncertainty

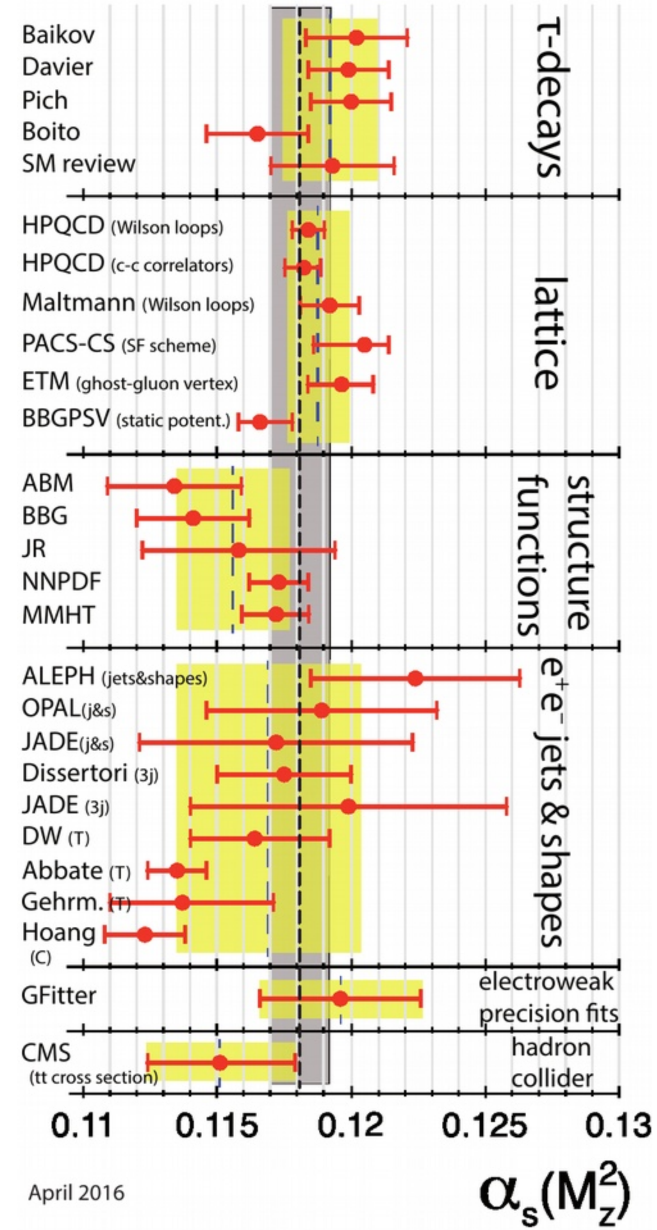
- Compare to:
  relative uncertainty of the fine structure constant:
  ~$2.3 \cdot 10^{-8}$ % [CODATA]

Uncertainty on α_s

- leads to non-negligible uncertainties on many observables
- Notable examples:
  Higgs production cross sections, branching ratios, ...

Jet measurements

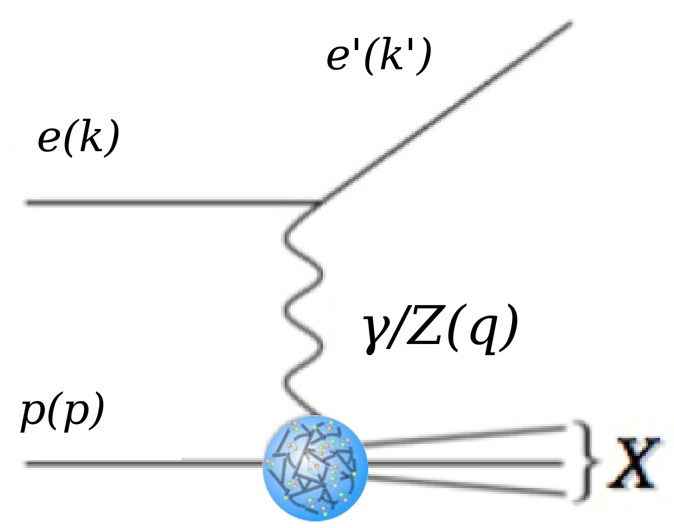
- Direct constraint on α_s
- So far no NNLO results available



Deep-inelastic *ep* scattering

Neutral current scattering (NC)

$$ep \to e'X$$



HERA *ep* collider in Hamburg

Kinematic variables

Photon virtuality

$$Q^2 = -q^2 = -(k-k')^2$$

Inelasticity

$$y = \frac{p \cdot q}{p \cdot k}$$

Data taking periods

- HERA I: 1994 – 2000
- HERA II: 2003 – 2007
- $\sqrt{s}$ = 300 or 319 GeV

H1 Experiment at HERA

H1 multi-purpose detector

Asymmetric design

Trackers

- Silicon tracker
- Jet chambers
- Proportional chambers

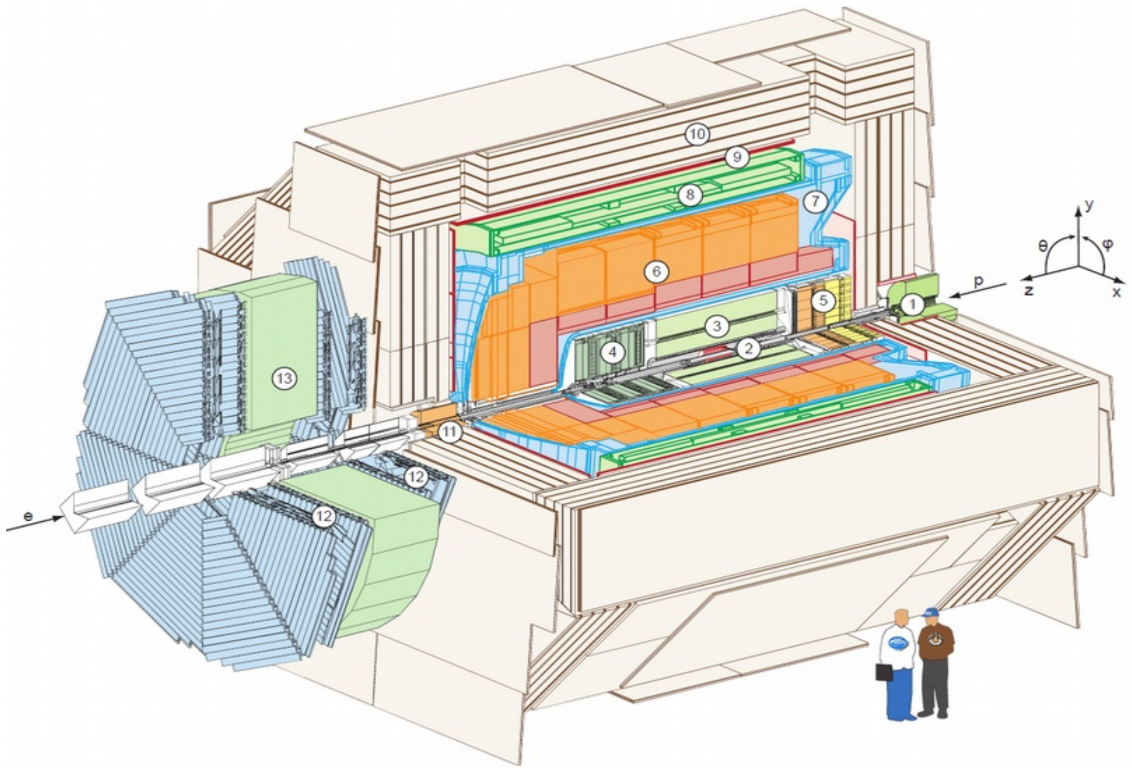
Calorimeters

- Liquid Argon sampling calorimeter
- SpaCal: scintillating fiber calorimeter

Superconducting solenoid

- 1.15T magnetic field

Muon detectors

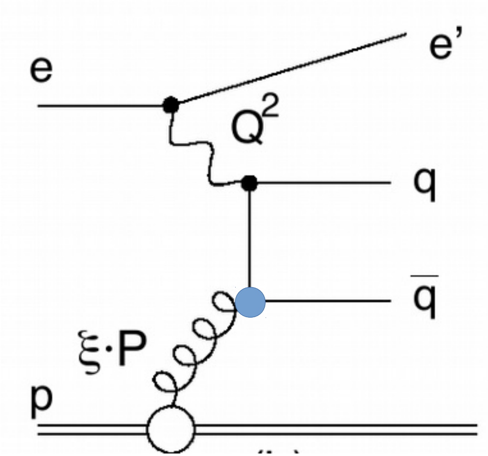


Drawing of the H1 experiment

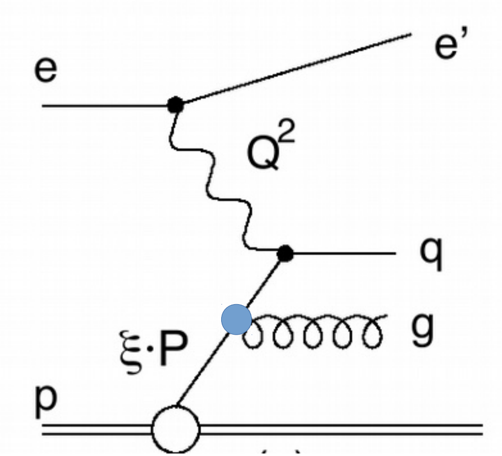
High experimental precision

- Overconstrained system in NC DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%
- Luminosity: 1.5 - 2.5%
- Continuous upgrades with time

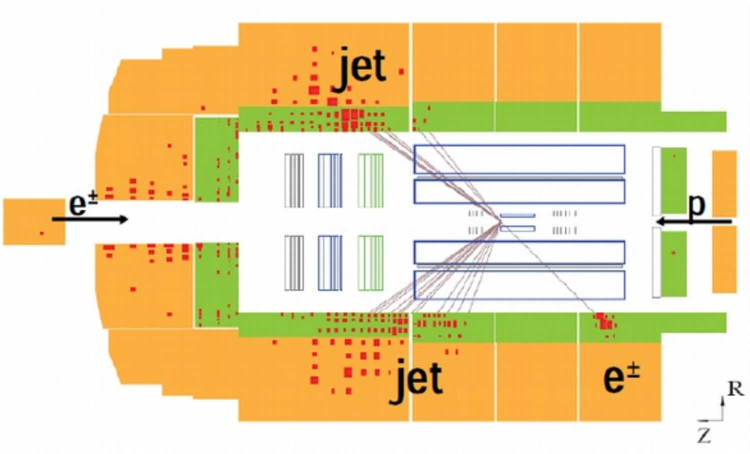
Jet production in DIS



Boson-gluon fusion



QCD Compton

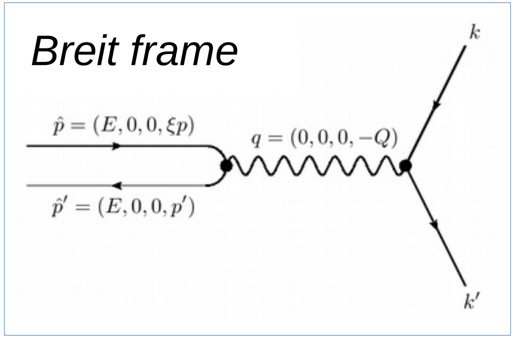


Exemplary event display

Jets in DIS measured in Breit frame

- ep -> 2jets
- Virtual boson collides 'head-on' with parton from proton
- Boson-gluon fusion dominant process
  QCD compton important only for high-p_T jets (high-x)

Jet measurement sensitive to α_s and gluon density



Inclusive jet cross sections by H1

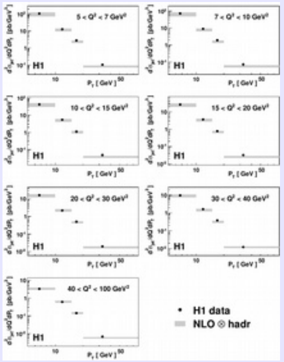
Inclusive jet cross sections

- $d\sigma/dQ^2dP_T^{jet}$
- 300 GeV, HERA-I & HERA-II
- low-Q^2 (<100 GeV^2) and high-Q^2 (>150 GeV^2) regions

Consistency

- kt-algorithm, R=1
- $-1.0 < \eta < 2.5$
- P_T ranges from 4.5 to 50 GeV

HERA-I low-Q^2



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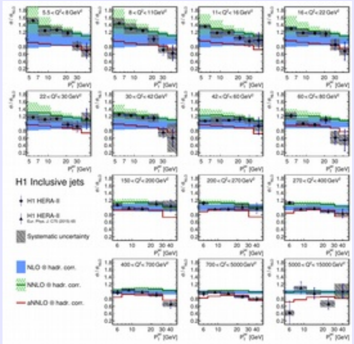
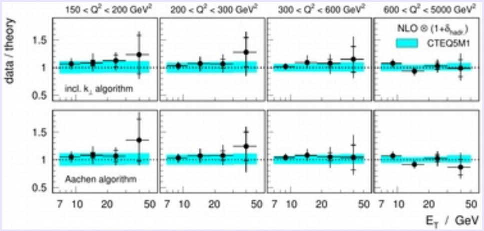
HERA-II low-Q^2



arXiv:1611.03421

300 GeV high-Q^2



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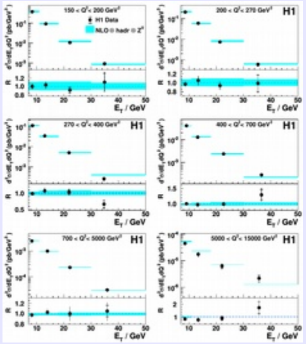
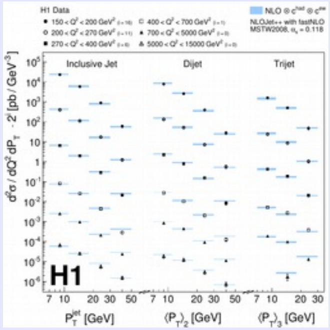
HERA-I high-Q^2



Phys.Lett.B653 (2007) 134

HERA-II high-Q^2



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arXiv:1611.03421

Dijet cross section by H1

Dijet cross sections

- $d\sigma/dQ^2 d\langle p_T\rangle$
- 300 GeV, HERA-I & HERA-II
- low-Q^2 and high-Q^2

Dijet definitions

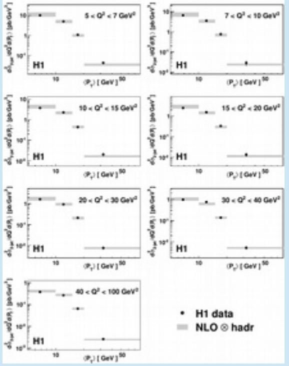
- $\langle p_T\rangle$ greater than 5,7 or 8.5 GeV
- P_T jet greater 4, 5 or 7 GeV
- Asymmetric cuts on p_T^{jet1} and p_T^{jet2}
- M_{12} cut for two data sets

Earlier studies

- All inclusive jet and dijet data have been employed for α_s extractions in NLO previously

-> Data and uncertainties well-understood
-> NNLO theory is new

HERA-I low-Q^2



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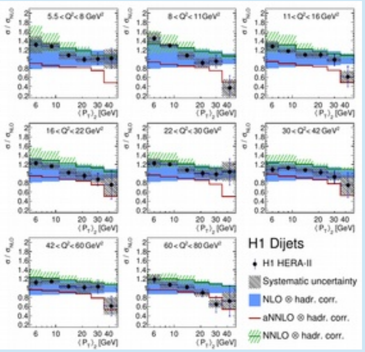
HERA-II low-Q^2



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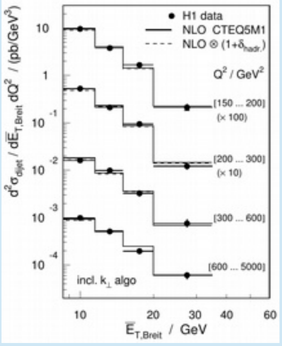
300 GeV high-Q^2



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HERA-I high-Q^2

Dijet cross sections not statistically independent from HERA-II analysis

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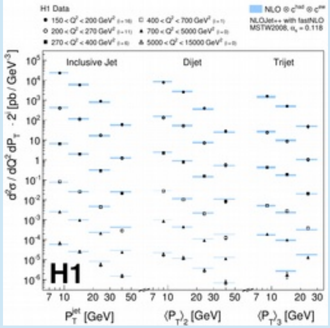
HERA-II high-Q^2



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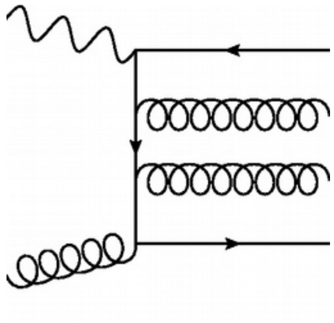
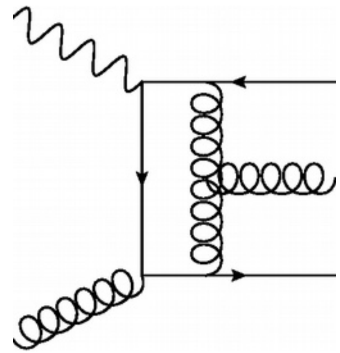
DIS jet production in NNLO

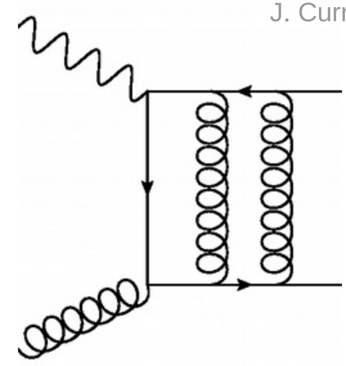
J. Curie, et al. [RPL 117 (2016) 042001]
J. Curie, et al. [JHEP 1707 (2017) 018]



Double-real



Real-virtual



Double-virtual

$$d\sigma^{RR,S}_{NNLO} \approx \underbrace{X(\{p_X\})}_{\text{antenna}}\overbrace{d\Phi_3(\{p_X\})}^{\text{Antenna PS}} \times \underbrace{|\mathcal{M}(\{\widetilde{p_m}\})|^2}_{\text{reduced ME}}\overbrace{d\Phi_m(\{\widetilde{p_m}\})}^{\text{reduced PS}} \times \underbrace{\mathcal{J}(\{\widetilde{p_m}\})}_{\text{jet function}}$$

A bit of history

- 1973 asymptotic freedom of QCD
  [PRL 30(1973) 1343 & 1346]
- 1993 NLO studies of DIS jet cross sections
  [Phys. Rev. D49 (1994) 3291]
- 2016 NNLO corrections for DIS jets
  [Phys. Rev. Lett. 117 (2016) 042001], [arXiv:1703.05977]

Antenna subtraction

- Cancellation of IR divergences with local subtraction terms
- Construction of (local) counter terms
- Move IR divergences across different phase space multiplicities

Scale dependence of NNLO cross sections

NNLO scale study

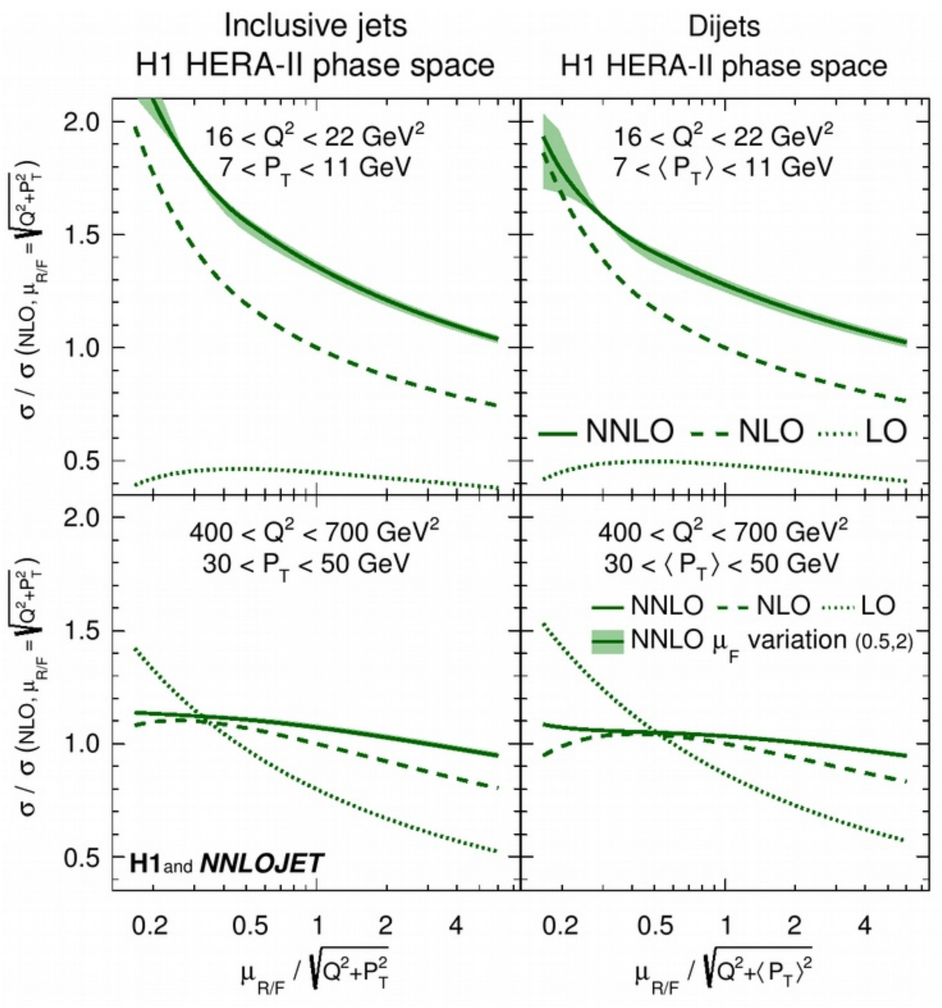
- Smultaneous variation of renormalisation and factorisation scale

At lower scales

- Significant NNLO k-factors
- Reduced scale dependence in NNLO
- Still relevant NNLO scale dependence
- Inclusive jets with higher scale dependence than dijets at lower scales

At higher scales

- NNLO with reduced scale dependence
- μ_f dependence very small



α_s-fit methodology

α_s determined in χ_2-minimisation

- $\alpha_s(m_Z)$ is a free parameter to NNLO theory prediction σ_i

$$\chi^2 = \sum_{i,j} \log \frac{\varsigma_i}{\sigma_i} (V_{\mathrm{exp}} + V_{\mathrm{had}} + V_{\mathrm{PDF}})^{-1}_{ij} \log \frac{\varsigma_j}{\sigma_j}$$

ς_i	H1 jet data
σ_i	NNLO theory
V	covariance matrices

- NNLO theory is sensitive to $\alpha_s(m_Z)$

$$\sigma_i = \sum_{k=g,q,\overline{q}} \int dx\, f_k(x, \mu_{\mathrm{F}}) \hat{\sigma}_{i,k}(x, \mu_{\mathrm{R}}, \mu_{\mathrm{F}}) \cdot c_{\mathrm{had},i}$$

$\sigma_i = \sigma_i(\alpha_s(m_Z))$
$f_k = f_k(P(\alpha_s(m_Z))$

Perform fits to

- All <u>inclusive jet data</u> sets (137 data points)
- All <u>dijet data</u> sets (103 data points)
- All <u>H1 jet data taken together</u> (denoted as 'H1 jets')
  (exclude HERA-I dijet data as correlations to inclusive jets are not known)

Strong coupling in NNLO from jets

α_s results from individual data sets

- High experimental precision
- Scale uncertainty is largest (theory) error
- All fits with good χ^2 -> consistency of data

Main result

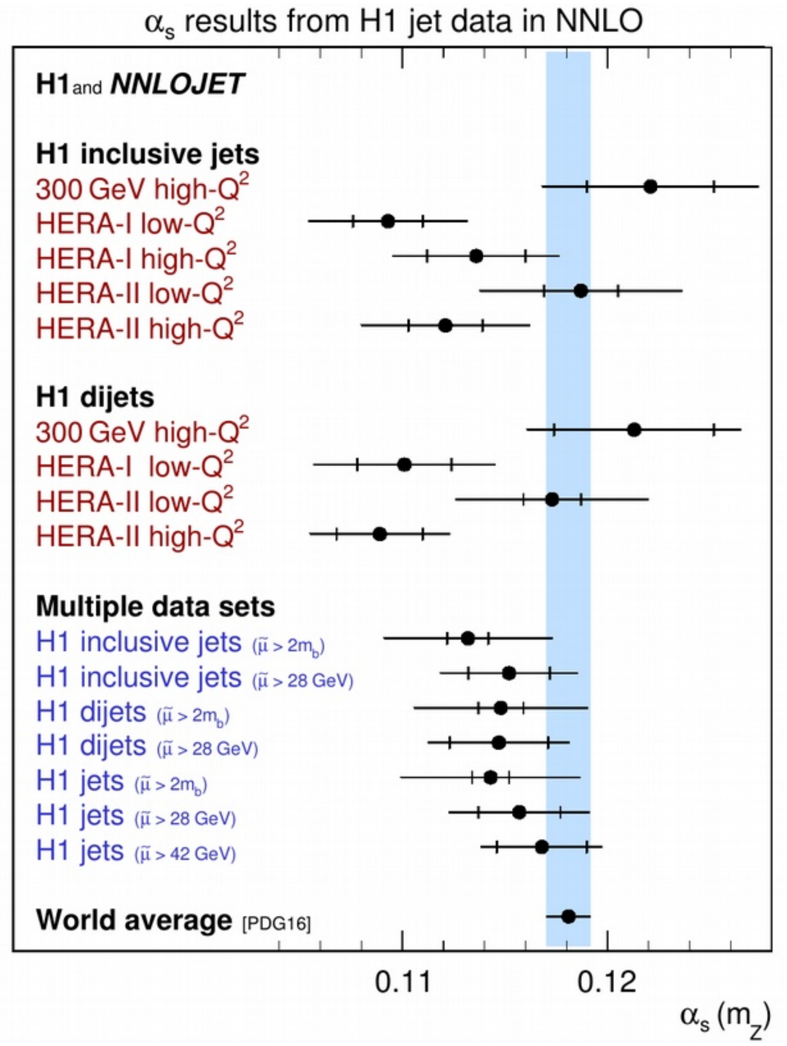
- Inclusive jets & dijets μ>28GeV, 91 data points

$$\alpha_s(m_Z) = 0.1157\,(20)_{\rm exp}\,(6)_{\rm had}\,(3)_{\rm PDF}\,(2)_{{\rm PDF}\alpha_s}\,(3)_{\rm PDFset}\,(27)_{\rm scale}$$

- Moderate exp. precision (due to μ>28GeV)
- Scale uncertainty dominates
- PDF uncertainties negligible

Smallest exp. uncertainty

- Fit to all data: $\Delta\alpha_s$ = $(9)_{exp}$



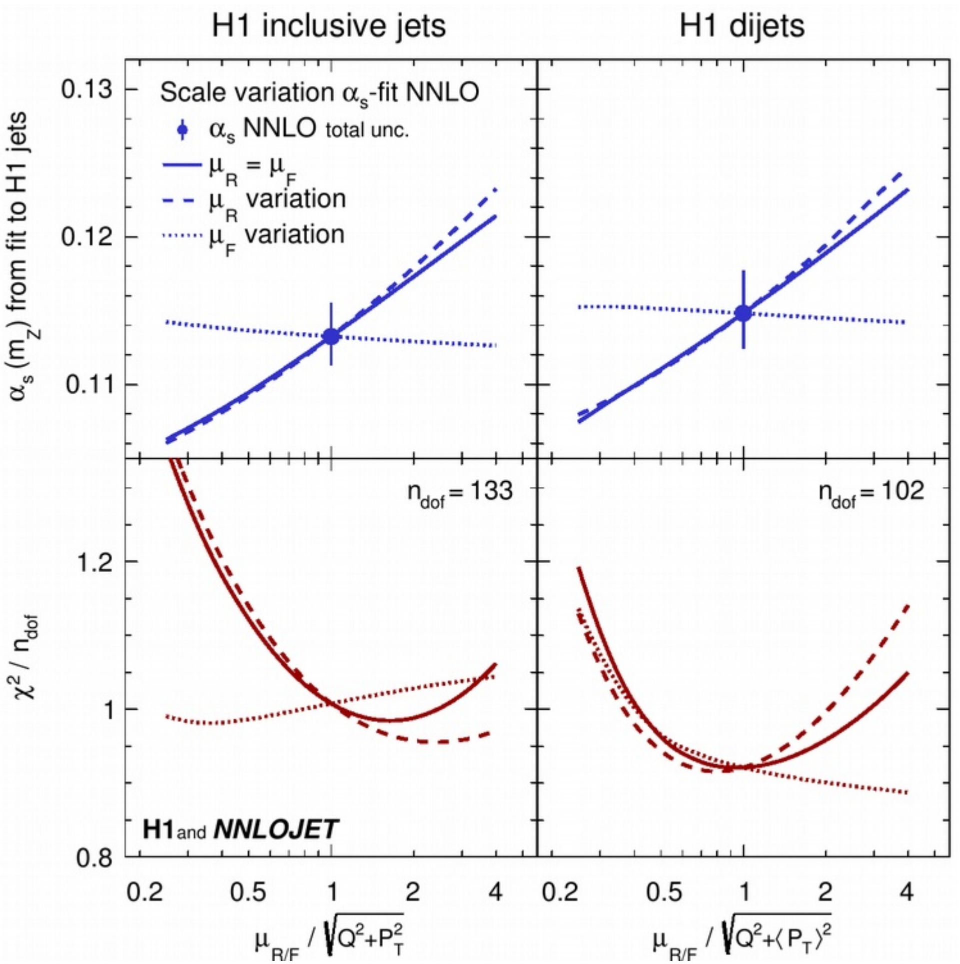
Scale dependence of α_s fit

α_s results as a function of scale factors

- Smooth results for all studied scale variations
- μ_R variation with more impact than μ_F

χ^2 values

- somewhat a 'technical parameter'
  -> not intended to be a parabolas
- χ^2 values increase for large scale factors
  -> large scale factors disvafored
- scale choice appears to be reasonable



Scale choice for α_s fit

Functional form for scales (μ_r, μ_f)

- Study various scales built from Q^2 and p_T
- 'p_T' refers to: p_T^{jet} or $<p_T>$

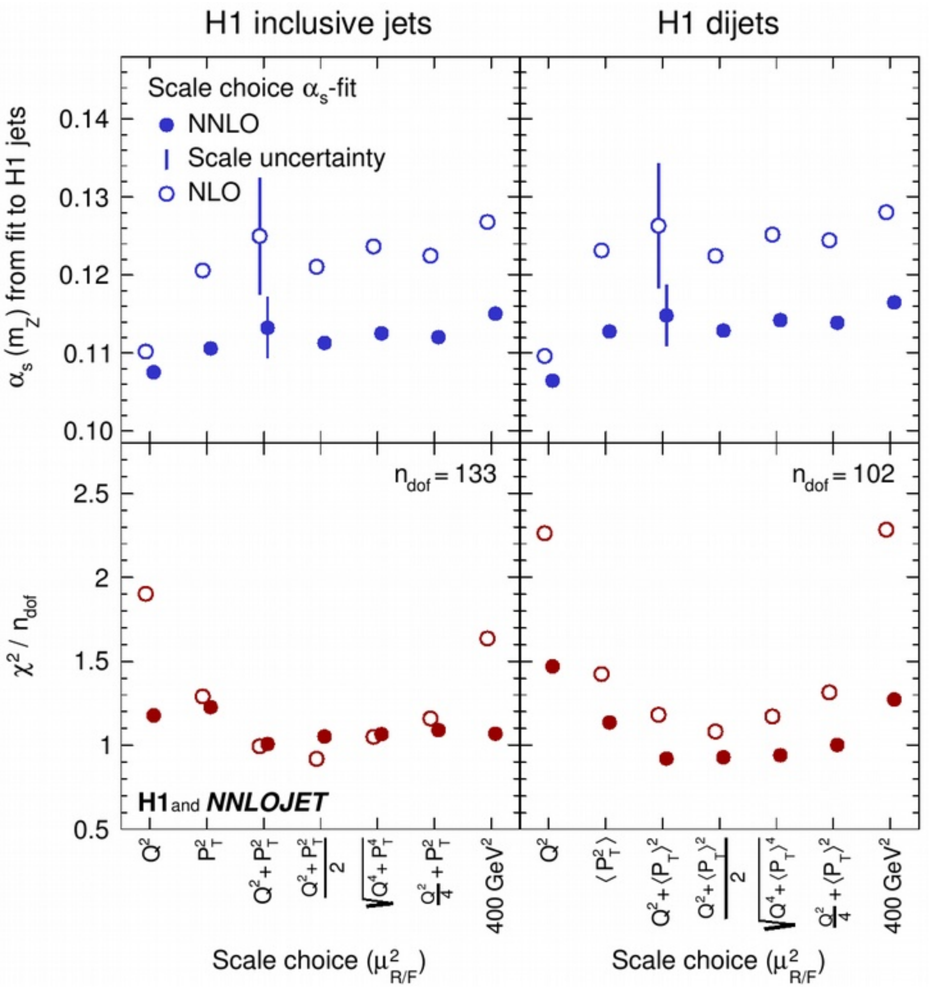
α_s results and χ^2 values

- Spread of results covered by scale uncertainty
- χ^2 values are similar for different choices
  -> NNLO with small 'scale dependence'

Use of only NLO matrix elements

- Large scale uncertainty
- Large dependence of result on scale choice
- Mainly larger χ^2 values than NNLO
- Larger fluctuation of χ^2 values than NNLO

NNLO with reduced scale dependence



Dependence on the PDF

PDF is an external input to NNLO calculation

PDF fitting groups differ

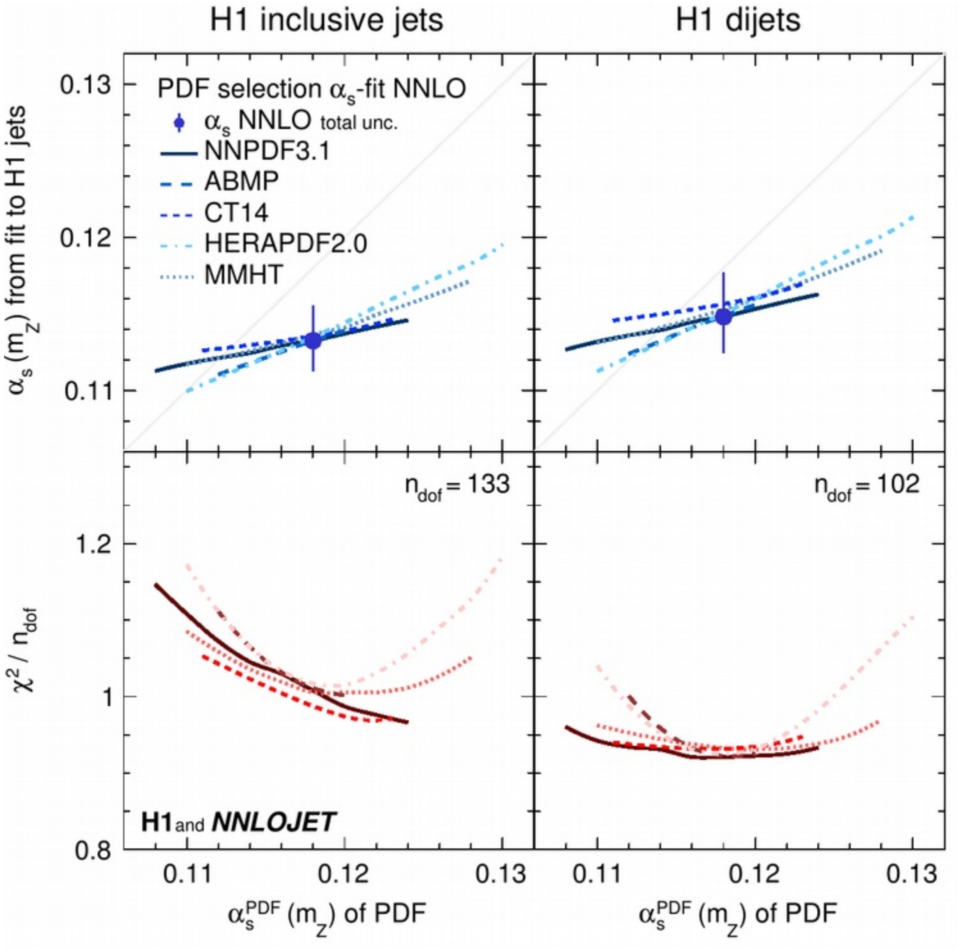
- choice of input data sets, PDF parameterisations, model parameters, fit methodology, etc...
- Though: different PDFs appear to be quite consistent

Choice of α_s for PDF determination

- $\alpha_s(m_Z)$ important input parameter to PDF fit
- Small correlation with fitted results

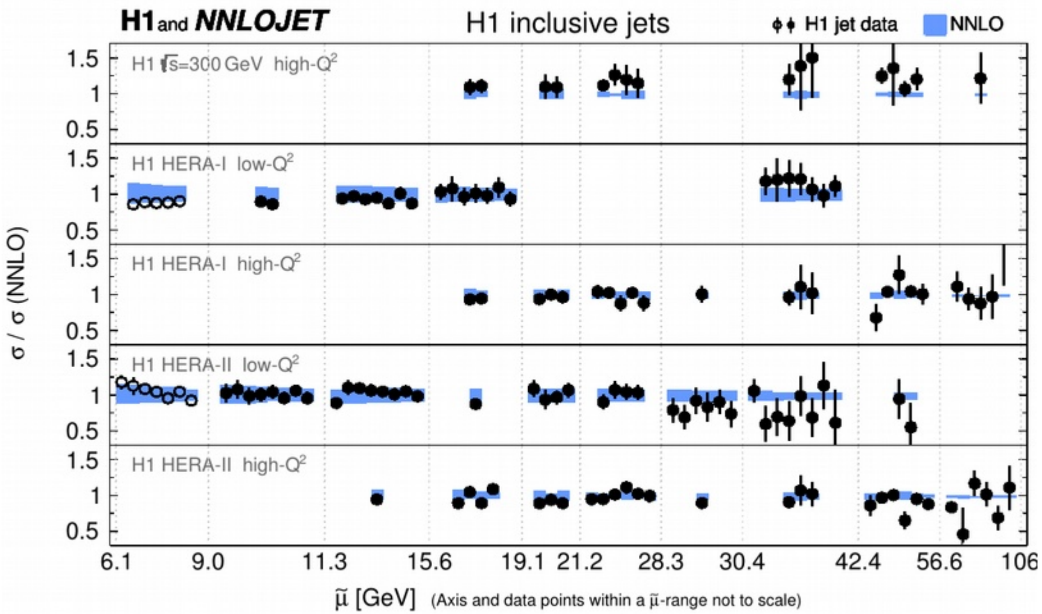
Our α_s result

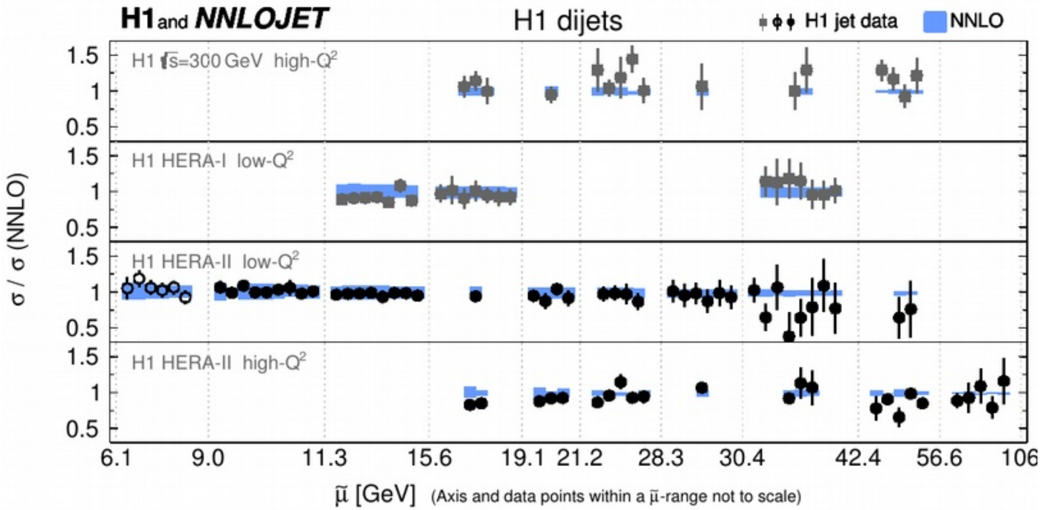
- almost independent on PDF assumptions



Comparison of NNLO predictions with data

- All H1 jet cross section data compared to NNLO predictions
  - Inclusive jets
  - Dijets
- Overall good agreement
  - NNLO describes all data very well
  - Also justified of course by good χ^2 values of the fits
- Great success of pQCD





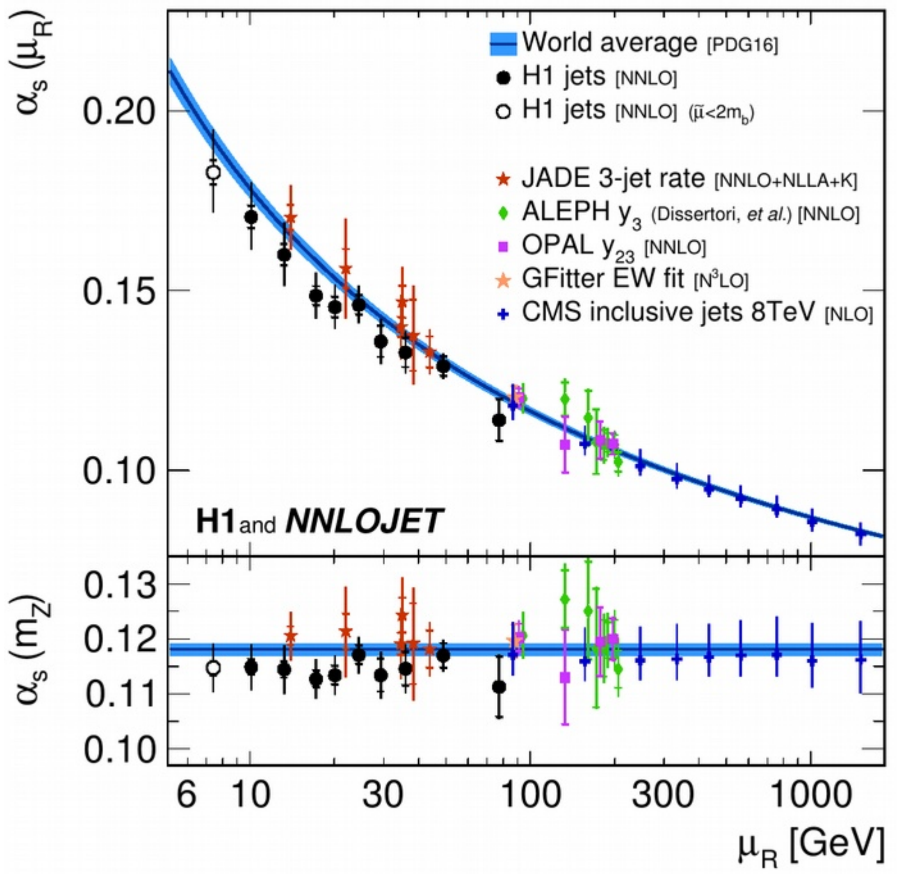
Tests of running of strong coupling

Test running of strong coupling

- Perform fits to <u>groups of data points</u> at similar scale
- Assumes running to be valid within the limited range covered by interval
- All fits have good χ^2

Results

- Consistency with expectation at all scales
- Scale uncertainty dominates at lower μ
- Consistency of inclusive jets and dijets (backup)



Most precise test in range $7 < \mu < 90$ GeV

Alternative α_s fitting approach

'PDF+α_s-fit'

H1PDF2017

Alternative α_s fitting approach: 'PDF+α_s-fit'

Simultaneous fit PDFs and α_s

- PDFs are predominantly determined from H1 inclusive DIS data

Perform H1 alone PDF fit: H1PDF2017

- Use (all) H1 inclusive DIS data
- Use (all) H1 normalised jet cross section data

-> 1529 data points

Normalised jet cross sections

- Jet cross sections normalised to inclusive DIS
- Correlations of jets and inclusive DIS cancel

PDFs are parameterised as

$$xf(x)|_{\mu_0} = f_A x^{f_B}(1-x)^{f_C}(1+f_D x + f_E x^2)$$

Cross section: ~ PDF ⊗σ

$$\sigma_i = \sum_{k=g,q,\overline{q}} \int dx f_k(x,\mu_\mathrm{F})\hat{\sigma}_{i,k}(x,\mu_\mathrm{R},\mu_\mathrm{F}) \cdot c_{\mathrm{had},i}$$

Normalised jets

Data set [ref.]	Q^2 domain	Inclusive jets	Dijets	Normalised inclusive jets	Normalised dijets	Stat. corr. between samples
300 GeV [17]	high-Q^2	✓	✓	–	–	–
HERA-I [23]	low-Q^2	✓	✓	–	–	–
HERA-I [21]	high-Q^2	✓	–	✓	–	–
HERA-II [15]	low-Q^2	✓	✓	✓	✓	✓
HERA-II [15, 24]	high-Q^2	✓	✓	✓	✓	✓

Inclusive NC & CC DIS

Data set [ref.]	Lepton type	$\sqrt{s}$ [GeV]	Q^2 range [GeV^2]	NC cross sections	CC cross sections	Lepton beam polarisation
Combined low-Q^2 [64]	e^+	301,319	(0.5) 12 – 150	✓	–	–
Combined low-E_p [64]	e^+	225,252	(1.5) 12 – 90	✓	–	–
94 – 97 [61]	e^+	301	150 – 30 000	✓	✓	–
98 – 99 [62, 63]	e^-	319	150 – 30 000	✓	✓	–
99 – 00 [63]	e^+	319	150 – 30 000	✓	✓	–
HERA-II [65]	e^+	319	120 – 30 000	✓	✓	✓
HERA-II [65]	e^-	319	120 – 50 000	✓	✓	✓

PDF+α_s-fit – H1PDF2017 [NNLO]

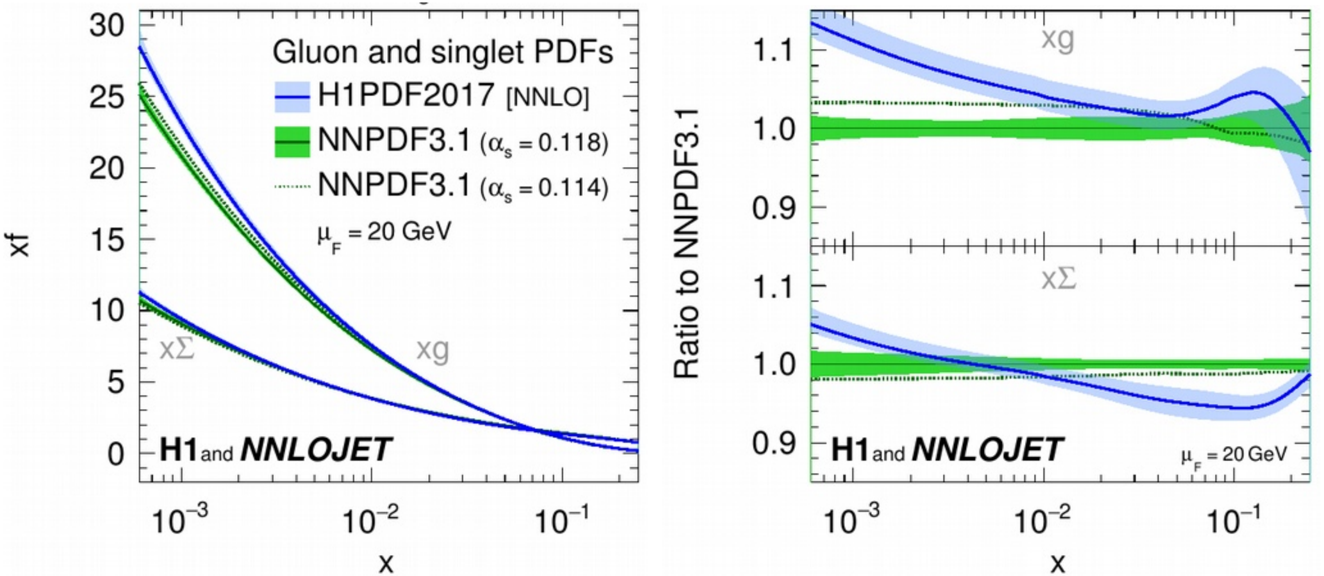
Result for PDFs

- Set of PDFs determined with high precision
- Despite α_s is a <u>free parameter</u> to the fit: precision is competitive with gloabl PDF fitters
- Gluon at lower *x*-values tends to be higher -> nowadays: also favored by small-x resummed PDFs

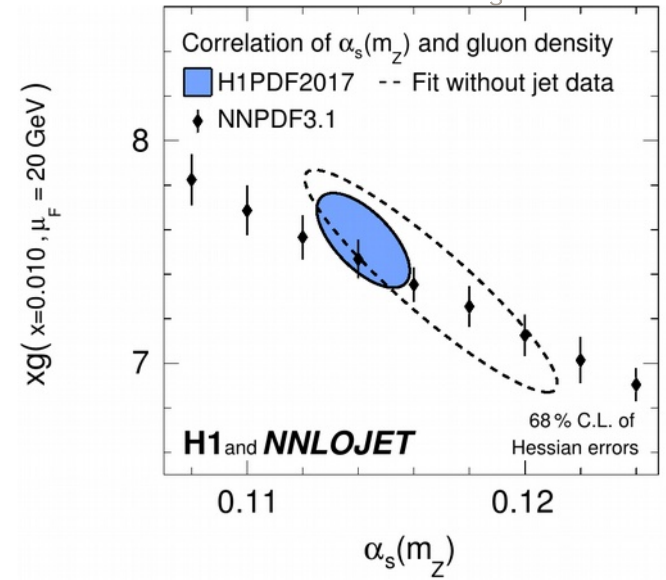
PDF+α_s-fit

- Using H1 jet data allows a precise determination of the <u>gluon PDF</u> and <u>α_s</u>
- χ^2/ndf ~ 1.01

Comparison of H1PDF2017 and NNPDF3.1



Correlation of α_s and g



Results

α_s determined in PDF+α_s-fit

$$\alpha_s(m_Z) = 0.1142\,(11)_{\text{exp,had,PDF}}\,(2)_{\text{mod}}\,(2)_{\text{par}}\,(26)_{\text{scale}}$$

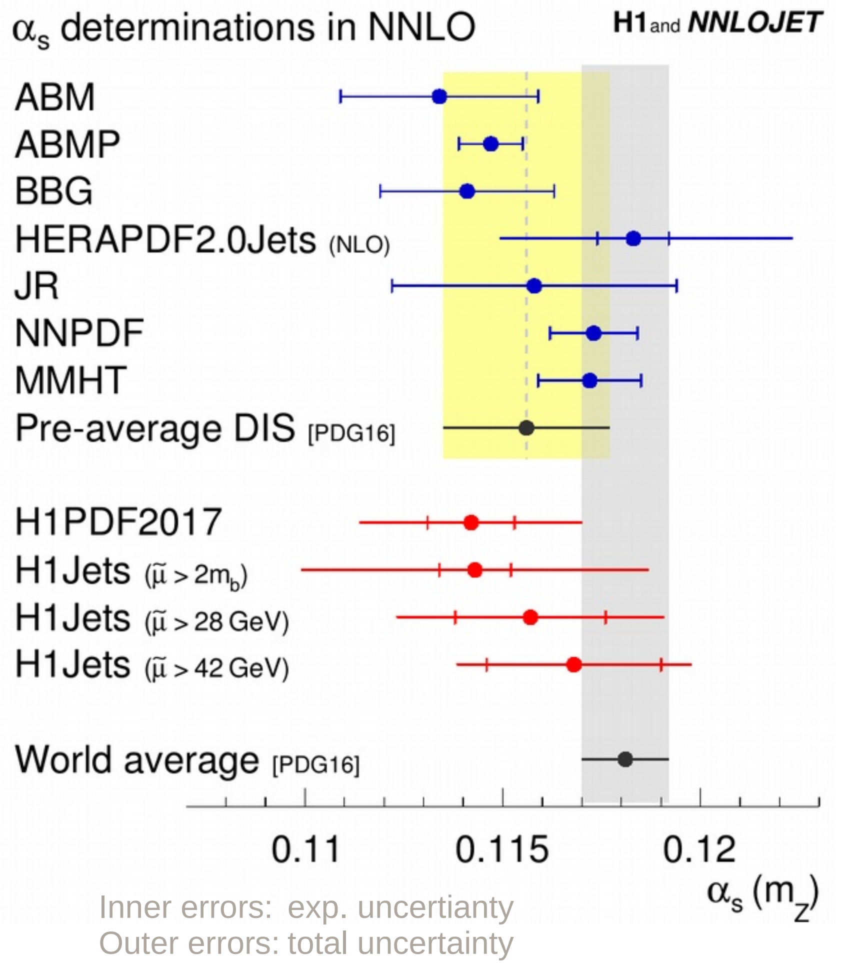
- High experimental precision
- Moderate theory uncertainty from NNLO

Comparison

- Higher precision than most of other (comparable) determinations
  -> PDF groups commonly determine exp. uncertainties (only)
  -> We further estimate scale uncertainties

- All H1 results consistent
- Results competitive with world average

- All results from DIS data tend to be lower than world average value



Conclusions

All H1 jet data confronted with NNLO predictions

- NNLO provides improved description w.r.t. NLO
- Quantitative comparison of all data
- NNLO predictions studied in great detail

NNLO used for determination of $\alpha_s(m_Z)$

- α_s-fit $$\alpha_{\mathrm{s}}(m_{\mathrm{Z}}) = 0.1157\,(20)_{\mathrm{exp}}\,(6)_{\mathrm{had}}\,(3)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha_{\mathrm{s}}}\,(3)_{\mathrm{PDFset}}\,(27)_{\mathrm{scale}}$$
- α_s+PDF-fit $$\alpha_{\mathrm{s}}(m_{\mathrm{Z}}) = 0.1142\,(11)_{\mathrm{exp,had,PDF}}\,(2)_{\mathrm{mod}}\,(2)_{\mathrm{par}}\,(26)_{\mathrm{scale}}$$
- High experimental and theoretical precision

NNLO predictions for jets are used for PDF fits for the first time

- Successful determination of gluon-density and $\alpha_s(m_Z)$ simultaneously
- Competitive precision of PDFs and $\alpha_s(m_Z)$

Fruitful collaboration of theoreticians and experimentalists (H1 & NNLOJET)

Study of total uncertainty

Scale uncertainties at various scales μ

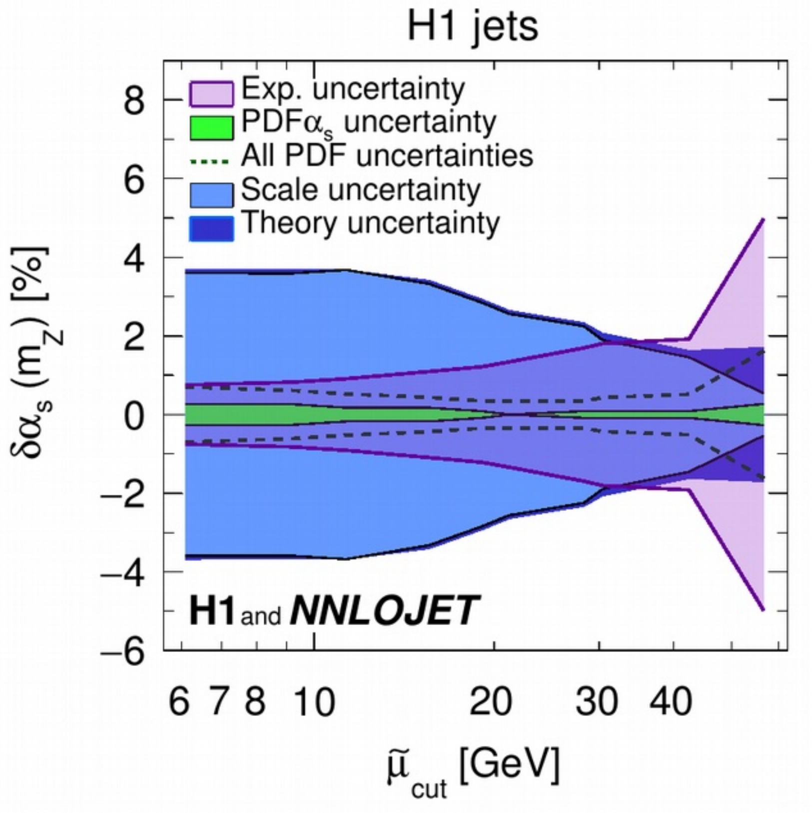
- At low-μ: large scale uncertainties...
- ... but also high sensitivity to $\alpha_s(m_Z)$

Fits imposing a cut on scale μ

- Repeat α_s fits:
  successively cut away data below μ_{cut}

Results

- Scale uncertainty decreases with μ_{cut}
- Exp. uncetainty increases with μ_{cut}



Cut on μ can balance between exp. and theoretical uncertainties at constant total precision

$\alpha_s(m_Z)$ dependence of cross sections

Jet cross sections directly sensitive to α_s

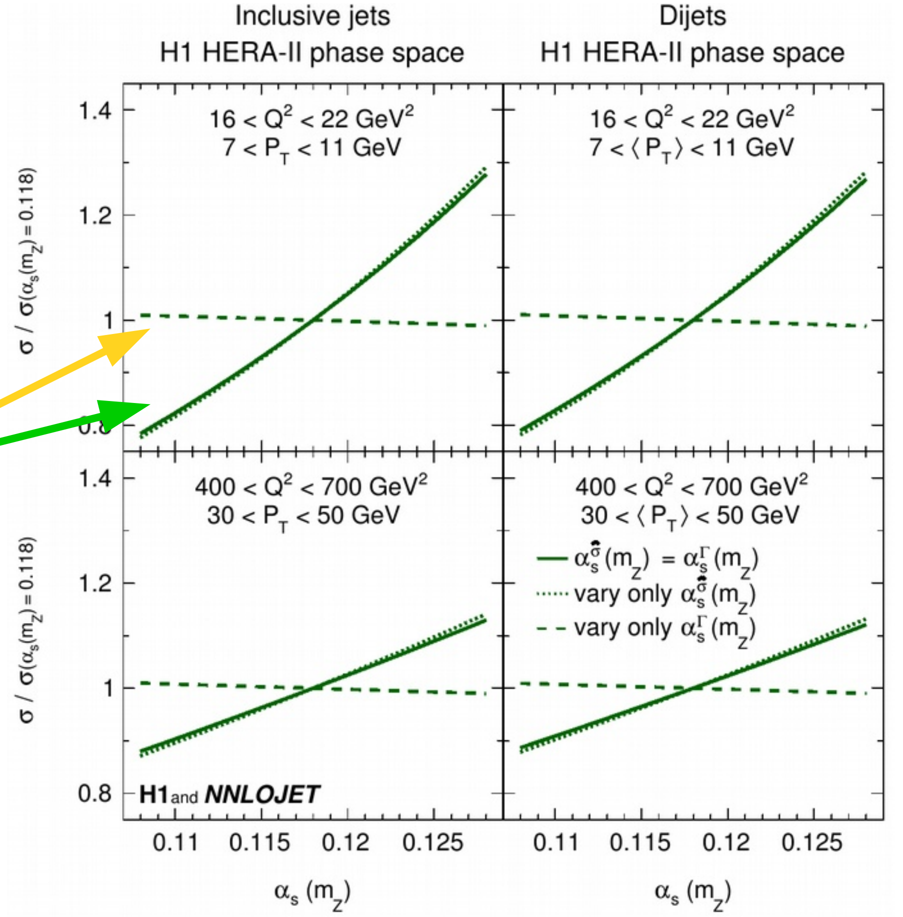
$$\sigma_i = \sum_{n=1}^{\infty} \sum_{k=g,q,\bar{q}} \int dx\, f_k(x,\mu_F)\,\hat{\sigma}^{(n)}_{i,k}(x,\mu_R,\mu_F) \cdot c_{\mathrm{had}}$$

Two α_s-dependencies

PDFs $\frac{\partial f}{\partial \alpha_s} = \frac{\mathcal{P} \otimes f}{\beta}$

Hard ME's
$\hat{\sigma}^{(n)}_{i,k} = \alpha_s^n(\mu_R)\tilde{\sigma}^{(n)}_{i,k}(x,\mu_R,\mu_F)$

- *Predominant α_s-sensitivity from ME's*
- *PDF's with almost negligible sensitivity*



α_s dependencies separately fitted

Fits to

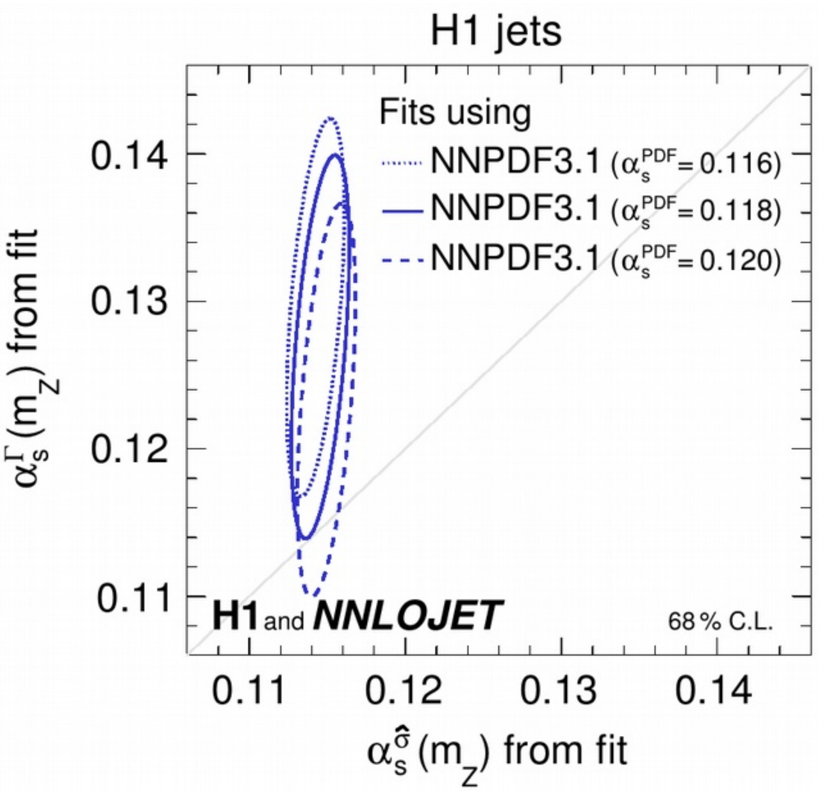
- Inclusive jet and dijet data fitted together
- Fits performed for different PDFs

Fits with two free α_s parameters

$$\sigma_i = f(\alpha_s^f(m_Z)) \otimes \hat{\sigma}_k(\alpha_s^{\hat{\sigma}}(m_Z)) \cdot c_{\text{had}}$$

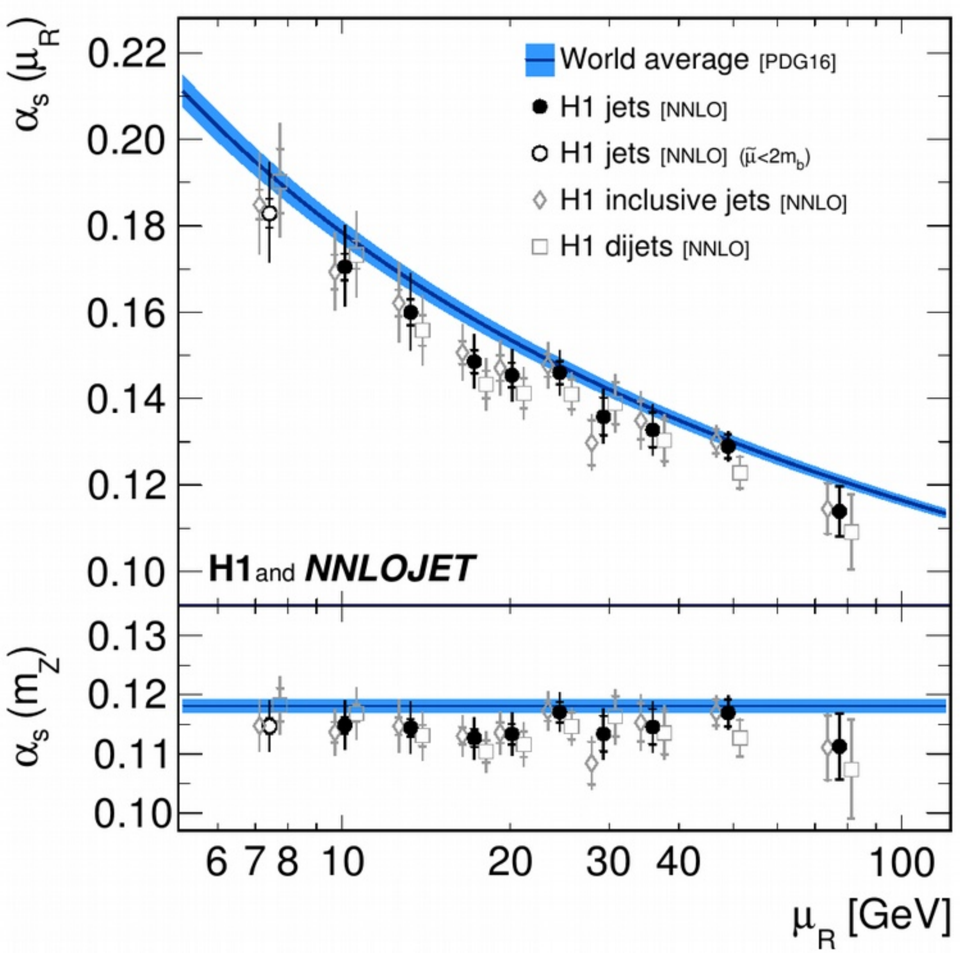
Results

- Most sensitivity arises from matrix elements
- Best-fit α_s-values in PDF's and ME's are consistent
- Anti-correlation between $\alpha_s^{PDF}(m_Z)$ and $\alpha_s^{\Gamma}(m_Z)$



$\alpha_s(m_Z)$ values from H1 jet cross sections

Data	$\tilde{\mu}_{\mathrm{cut}}$	$\alpha_s(m_Z)$ with uncertainties	th	tot	χ^2/n_{dof}
Inclusive jets					
300 GeV high-Q^2	$2m_b$	$0.1221\,(31)_{\mathrm{exp}}\,(22)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(3)_{\mathrm{PDF}\alpha_s}\,(4)_{\mathrm{PDFset}}\,(36)_{\mathrm{scale}}$	$(43)_{\mathrm{th}}$	$(53)_{\mathrm{tot}}$	6.5/15
HERA-I low-Q^2	$2m_b$	$0.1093\,(17)_{\mathrm{exp}}\,(8)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(5)_{\mathrm{PDF}\alpha_s}\,(7)_{\mathrm{PDFset}}\,(33)_{\mathrm{scale}}$	$(35)_{\mathrm{th}}$	$(39)_{\mathrm{tot}}$	17.5/22
HERA-I high-Q^2	$2m_b$	$0.1136\,(24)_{\mathrm{exp}}\,(9)_{\mathrm{had}}\,(6)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(4)_{\mathrm{PDFset}}\,(31)_{\mathrm{scale}}$	$(33)_{\mathrm{th}}$	$(41)_{\mathrm{tot}}$	14.7/23
HERA-II low-Q^2	$2m_b$	$0.1187\,(18)_{\mathrm{exp}}\,(8)_{\mathrm{had}}\,(4)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(45)_{\mathrm{scale}}$	$(46)_{\mathrm{th}}$	$(50)_{\mathrm{tot}}$	29.6/40
HERA-II high-Q^2	$2m_b$	$0.1121\,(18)_{\mathrm{exp}}\,(9)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(2)_{\mathrm{PDFset}}\,(35)_{\mathrm{scale}}$	$(37)_{\mathrm{th}}$	$(41)_{\mathrm{tot}}$	42.5/29
Dijets					
300 GeV high-Q^2	$2m_b$	$0.1213\,(39)_{\mathrm{exp}}\,(17)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(31)_{\mathrm{scale}}$	$(35)_{\mathrm{th}}$	$(52)_{\mathrm{tot}}$	13.6/15
HERA-I low-Q^2	$2m_b$	$0.1101\,(23)_{\mathrm{exp}}\,(8)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(5)_{\mathrm{PDFset}}\,(36)_{\mathrm{scale}}$	$(38)_{\mathrm{th}}$	$(45)_{\mathrm{tot}}$	10.4/20
HERA-II low-Q^2	$2m_b$	$0.1173\,(14)_{\mathrm{exp}}\,(9)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(5)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(44)_{\mathrm{scale}}$	$(45)_{\mathrm{th}}$	$(47)_{\mathrm{tot}}$	17.4/41
HERA-II high-Q^2	$2m_b$	$0.1089\,(21)_{\mathrm{exp}}\,(7)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(3)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(25)_{\mathrm{scale}}$	$(27)_{\mathrm{th}}$	$(34)_{\mathrm{tot}}$	28.0/23
H1 inclusive jets	$2m_b$	$0.1132\,(10)_{\mathrm{exp}}\,(5)_{\mathrm{had}}\,(4)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(2)_{\mathrm{PDFset}}\,(40)_{\mathrm{scale}}$	$(40)_{\mathrm{th}}$	$(42)_{\mathrm{tot}}$	134.0/133
H1 inclusive jets	28 GeV	$0.1152\,(20)_{\mathrm{exp}}\,(6)_{\mathrm{had}}\,(2)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(26)_{\mathrm{scale}}$	$(27)_{\mathrm{th}}$	$(33)_{\mathrm{tot}}$	44.1/60
H1 dijets	$2m_b$	$0.1148\,(11)_{\mathrm{exp}}\,(6)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(4)_{\mathrm{PDF}\alpha_s}\,(4)_{\mathrm{PDFset}}\,(40)_{\mathrm{scale}}$	$(41)_{\mathrm{th}}$	$(42)_{\mathrm{tot}}$	93.9/102
H1 dijets	28 GeV	$0.1147\,(24)_{\mathrm{exp}}\,(5)_{\mathrm{had}}\,(3)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(24)_{\mathrm{scale}}$	$(25)_{\mathrm{th}}$	$(35)_{\mathrm{tot}}$	30.8/43
H1 jets	$2m_b$	$0.1143\,(9)_{\mathrm{exp}}\,(6)_{\mathrm{had}}\,(5)_{\mathrm{PDF}}\,(5)_{\mathrm{PDF}\alpha_s}\,(4)_{\mathrm{PDFset}}\,(42)_{\mathrm{scale}}$	$(43)_{\mathrm{th}}$	$(44)_{\mathrm{tot}}$	195.0/199
H1 jets	28 GeV	$0.1157\,(20)_{\mathrm{exp}}\,(6)_{\mathrm{had}}\,(3)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha_s}\,(3)_{\mathrm{PDFset}}\,(27)_{\mathrm{scale}}$	$(28)_{\mathrm{th}}$	$(34)_{\mathrm{tot}}$	63.2/90
H1 jets	42 GeV	$0.1168\,(22)_{\mathrm{exp}}\,(7)_{\mathrm{had}}\,(2)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha_s}\,(5)_{\mathrm{PDFset}}\,(17)_{\mathrm{scale}}$	$(20)_{\mathrm{th}}$	$(30)_{\mathrm{tot}}$	37.6/40
H1PDF2017 [NNLO]	$2m_b$	$0.1142\,(11)_{\mathrm{exp,NP,PDF}}\,(2)_{\mathrm{mod}}\,(2)_{\mathrm{par}}\,(26)_{\mathrm{scale}}$		$(28)_{\mathrm{tot}}$	1539.7/1516



$\alpha_s(\mu_R)$
0.22
0.20
0.18
0.16
0.14
0.12
0.10
World average [PDG16]
H1 jets [NNLO]
H1 jets [NNLO] ($\tilde{\mu}$<2m$_b$)
H1 inclusive jets [NNLO]
H1 dijets [NNLO]
H1 and NNLOJET
$\alpha_s(m_Z)$
0.13
0.12
0.11
0.10
6 7 8 10
20
30 40
100
μ_R [GeV]

Data set [ref.]	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	DIS kinematic range	Inclusive jets	Dijets $n_{\mathrm{jets}} \geq 2$
300 GeV [17]	300	33	$150 < Q^2 < 5000\,\mathrm{GeV}^2$ $0.2 < y < 0.6$	$7 < P_{\mathrm{T}}^{\mathrm{jet}} < 50\,\mathrm{GeV}$	$P_{\mathrm{T}}^{\mathrm{jet}} > 7\,\mathrm{GeV}$ $8.5 < \langle P_{\mathrm{T}} \rangle < 35\,\mathrm{GeV}$
HERA-I [23]	319	43.5	$5 < Q^2 < 100\,\mathrm{GeV}^2$ $0.2 < y < 0.7$	$5 < P_{\mathrm{T}}^{\mathrm{jet}} < 80\,\mathrm{GeV}$	$5 < P_{\mathrm{T}}^{\mathrm{jet}} < 50\,\mathrm{GeV}$ $5 < \langle P_{\mathrm{T}} \rangle < 80\,\mathrm{GeV}$ $m_{12} > 18\,\mathrm{GeV}$ $(\langle P_{\mathrm{T}} \rangle > 7\,\mathrm{GeV})^*$
HERA-I [21]	319	65.4	$150 < Q^2 < 15000\,\mathrm{GeV}^2$ $0.2 < y < 0.7$	$5 < P_{\mathrm{T}}^{\mathrm{jet}} < 50\,\mathrm{GeV}$	–
HERA-II [15]	319	290	$5.5 < Q^2 < 80\,\mathrm{GeV}^2$ $0.2 < y < 0.6$	$4.5 < P_{\mathrm{T}}^{\mathrm{jet}} < 50\,\mathrm{GeV}$	$P_{\mathrm{T}}^{\mathrm{jet}} > 4\,\mathrm{GeV}$ $5 < \langle P_{\mathrm{T}} \rangle < 50\,\mathrm{GeV}$
HERA-II [15, 24]	319	351	$150 < Q^2 < 15000\,\mathrm{GeV}^2$ $0.2 < y < 0.7$	$5 < P_{\mathrm{T}}^{\mathrm{jet}} < 50\,\mathrm{GeV}$	$5 < P_{\mathrm{T}}^{\mathrm{jet}} < 50\,\mathrm{GeV}$ $7 < \langle P_{\mathrm{T}} \rangle < 50\,\mathrm{GeV}$ $m_{12} > 16\,\mathrm{GeV}$

Inclusive jet cross sections

Inclusive jet cross sections

- low Q^2: 4.5 < P_T < 50 GeV
- high Q^2: 5 < P_T < 50 GeV

Predictions

- NLO, aNNLO & NNLO

NLO

- Data well described within uncertainties

aNNLO

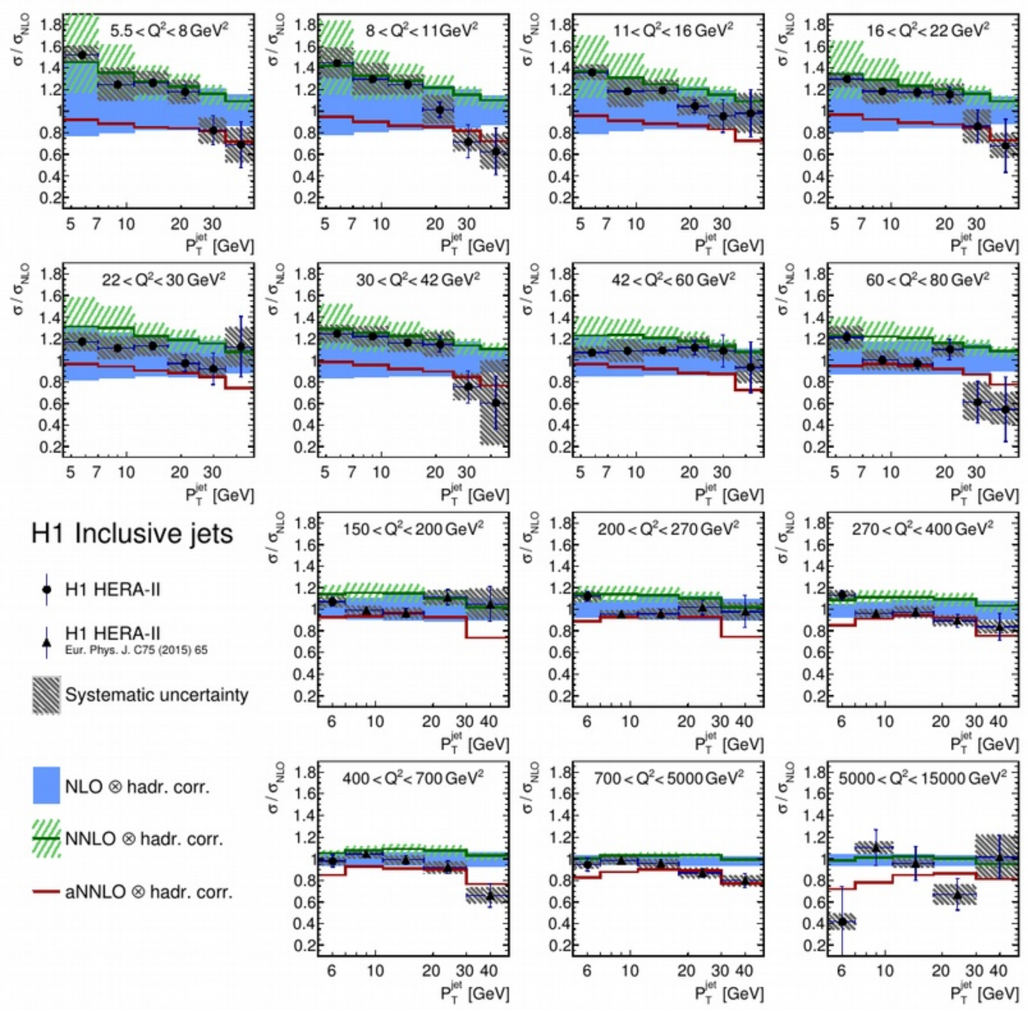
- Somewhat improved shape description

NNLO

- Improved shape and normalisation
- Reduced scale uncertainties for larger values of μ_r

Also measured

- Normalised inclusive jet cross sections



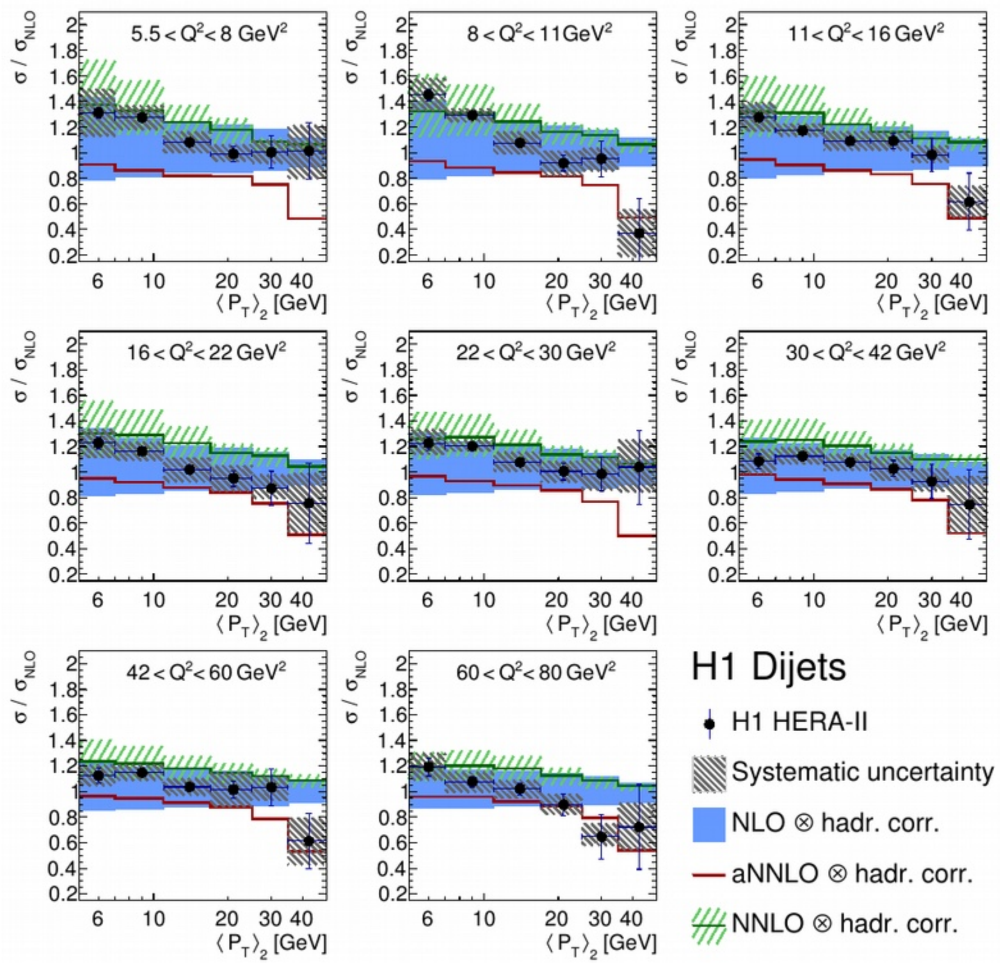
Ratio of dijet cross sections to NLO

Scale uncertainty

- So-called '7-point scale variation':
  Vary μ_r and μ_f independently by factors of 2 and 0.5, but exclude variations in 'opposite' directions

Ratio to NLO prediction

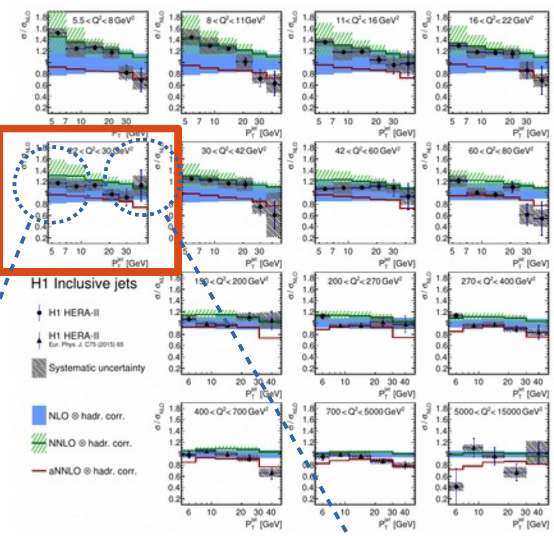
- NLO give reasonable descriptions within large scale uncertainties
- aNNLO improves shape
  - aNNLO expected to improve description at high <p_T>
- NNLO improves shape dependence
  - NNLO predictions have smaller scale uncertainties than NLO at high-<p_T>



Phenomenological application

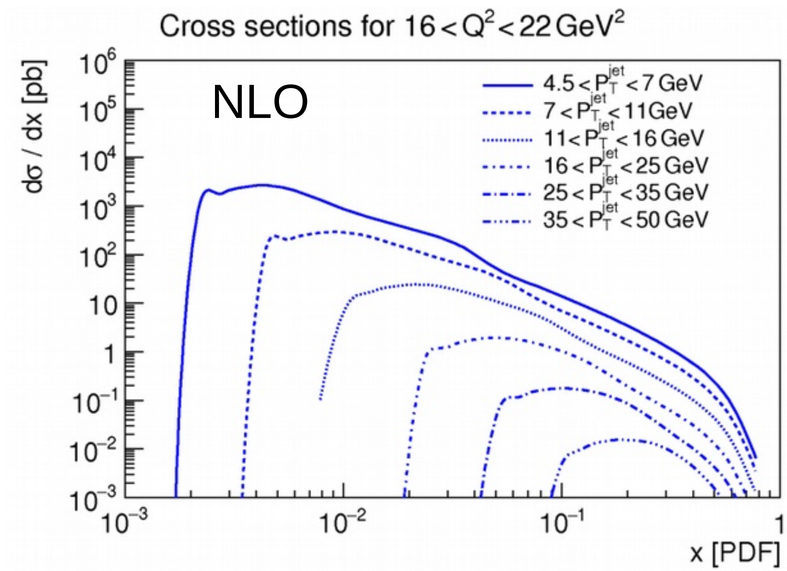
PDF dependence of <u>inclusive jet</u> cross sections

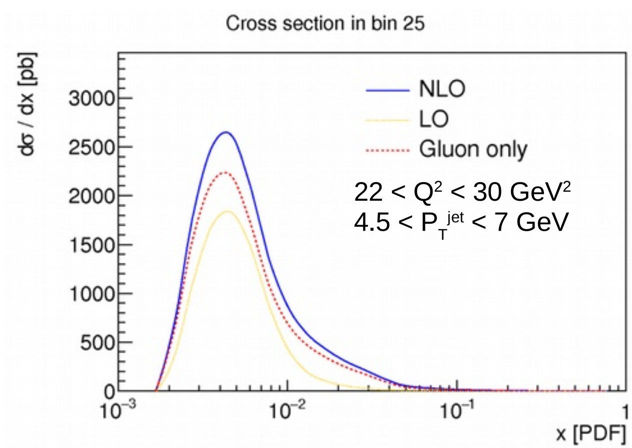
- Cross sections as a function of x_{PDF}
- P_T-bins probe different x-regions
  - Lowest x-values: $x \sim 10^{-3}$
  - High-P_T cross sections: $x > 10^{-1}$
- x-dependence shows little dependence on Q^2

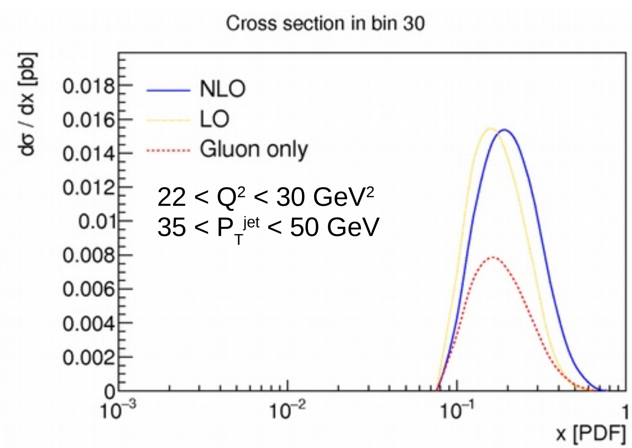


H1 jets may become important for PDFs

- high-x gluon
- only a single hadron involved (decorrelate high-x <--> low-x)



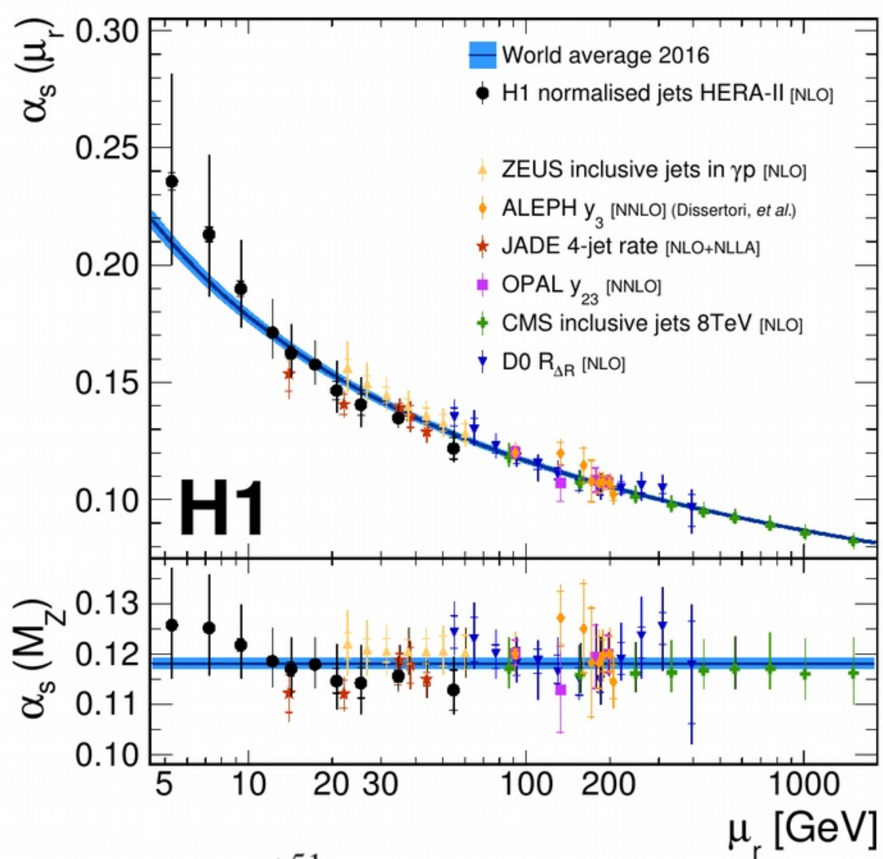




Determination of the strong coupling $\alpha_s(M_Z)$

Determination of $\alpha_s(M_Z)$ in a fit to H1 HERA-II jets

- Use low- and high-Q2 data
  - Low-Q2 jets [arxiv:1611.03421]
  - high-Q2 jets (Eur.Phys.J.C75 (2015) 2)
- Use all normalised jet cross sections
  - All correlations of uncertainties are known
- Fit $\alpha_s(M_Z)$ in χ^2-minimization procedure



Two results (NLO)

- Probe running of $\alpha_s(\mu_r)$
- One fit to all data points together: $\alpha_s(M_Z)$

$$\alpha_s(M_Z) = 0.1173\,(4)_{\rm exp}\,(3)_{\rm PDF}\,(7)_{\rm PDF(\alpha_s)}\,(11)_{\rm PDFset}\,(6)_{\rm had}\,(^{+51}_{-43})_{\rm scale}$$

World average (PDG2016)
$\alpha_s(M_Z) = 0.1181 \pm 0.0011$

- Very high experimental precision
- Future improvements on dominating theory uncertainties in NNLO